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Treatment for the Control of Organic Chemical Contamination of Drinking Water Cost and Performance

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TREATMENT FOR THE CONTROL OF ORGANIC CHEMICAL CONTAMINATION OF DRINKING WATER: COST AND PERFORMANCE

by

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This paper discusses several control technology options available to treat ground water for organic chemical contamination. A cost and performance analysis is presented in order to guide the selection of control technologies for three major contaminants: Trichloroethylene; Tetrachloroethylene; 1,1,1-Trichloroethane. In all cases aeration is the cheapest alternative for treatment. If adsorption is required, home units may prove to be cheaper then central adsorption treatment (GAC).

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INTRODUCTION

Contamination of drinking water by organic chemicals has become of increasing concern in the past few years. A particularly difficult and insidious problem is the contamination of ground water. Although the effort to learn how and where synthetic organic chemicals have contaminated ground-water is small, it is growing and it is now known that contamination has occurred at significant concentration levels. Contamination by synthetic organic chemicals is generally associated with where they are made, spilled, used or discarded.[1,2,3]

Historically, ground water has been viewed as a relatively pristine source and is generally used as a drinking water source without major treatment other than disinfection. However, recent data from EPA and State monitoring surveys indicate that a significant number of drinking water supplies derived from ground waters, as well as surface waters, contain some volatile organic chemicals. While surface waters subject to industrial contamination can contain a broad spectrum of synthetic organic chemicals,

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typically their concentrations would be in the low microgram per liter levels (e.g., less than 5 ug/L). Although only a small percentage of ground water supplies have been found to be contaminated by one, two or several discrete compounds, their concentrations can be much higher (e.g., 100 to 1000 ug/L).

Once a contaminated water supply has been identified, a range of options is open to the effected system. Since in many cases it may be impossible to develop a new, uncontaminated source of supply, EPA has investigated the performance and costs of certain treatment methods to apply where source control is infeasible. Methods for removal of these volatile organic chemicals include aeration and granular activated carbon.

This paper will discuss and evaluate preliminary design estimates for a hypothetical ground water contamination situation involving trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane. An examination will be made of the proper scale of application of aeration and adsorbtion, options for minimizing cost such as regionalization or installation of home units and the incremental costs of treatment for the technologies considered.

PERFORMANCE CHARACTERISTICS

In this section, the performance characteristics of the three types of technology that will be considered to remove volatile organics from ground water will be considered: granular activated carbon adsorption; tower aeration; and, diffused air aeration.[4]

Granular activated carbon (GAC) is an adsorption technique that is very effective for removing a broad spectrum of organics from drinking water. Table 1 summarizes the performance of GAC in pounds of carbon/thousand gallons of water required to remove the three volatile organics from a given influent

TABLE 1

ESTIMATED CARBON USAGE NECESSARY TO ACHIEVE DESIRED TREATMENT*

	Inf. Conc. ug/L	Desired Effluent Concentration, ug/L				
		0.1	1	10	50	100
Trichloroethylene	1000	6.9 (0.50)	8.7 (0.4)	10.4 (0.32)	11.6 (0.290	12.1 (0.28)
	100	16.7 (0.20)	22.1 (0.15)	27.7 (0.12)	31.5 (0.11)	-
	10	41.0 (0.08)	60.3 (0.06)	-	-	-
	1	96.1 (0.03)	-	-	-	-
1,1,1-Trichloroethane	1000	1.7 (2.0)	2.6 (1.3)	3.3 (1.0)	3.9 (0.86)	4.2 (0.80)
	100	8.1 (0.4)	13.0 (0.26)	18.0 (0.19)	21.0 (0.16)	-
	10	37.0 (0.09)	70.0 (0.05)	-	-	-
	1	169 (0.02)	-	-	-	-
Tetrachloroethylene	1000	14.7 (0.23)	20.7 (0.16)	26.7 (0.13)	30.9 (0.11)	32.7 (0.10)
	100	40.1 (0.08	59.6 (0.06)	81.2 (0.41)	100 (0.03)	-
	10	111 (0.03)	200 (0.02)	-	-	-
	1	306 (0.01)	-	-	-	-

*Mean GAC usage, 10^3 M^3 water/M^3 carbon (lb carbon/10^3 gal water).

concentration to a target effluent concentration. For example, for an influent concentration of trichloroethylene of 1000 ug/liter to be reduced to 1/10 of a ug/liter, the required carbon usage is .20 lbs of carbon/1000 gallons of water.

Table 2 summarizes the performance information required for using both diffused air aeration and tower aeration or stripping. The influent concentration in ug/L is given versus the effluent concentration to be achieved and the elements of the Table contain the required air-to-water ratio that is necessary to achieve that level of performance. For example, if we wish to reduce an influent concentration of trichlorethylene from 1000 ug/liter to .1 ug/liter the required air-to-water ratio is 76:1. These air-to-water ratios are for both diffused air aeration and tower stripping.

TABLE 2

ESTIMATED AIR TO WATER RATIOS NECESSARY TO ACHIEVE DESIRED TREATMENT

		Effluent Concentration, ug/L				
	Inf. Conc. ug/L	0.1	1	10	50	100
Trichloroethylene	1000	76:1	54:1	32:1	17:1	11:1
	100	54:1	32:1	11:1	1:1	-
	10	32:1	11:1	-	-	-
	1	11:1	-	-	-	-
Tetrachloroethylene	1000	96:1	72:1	45:1	26:1	18:1
	100	72:1	45:1	18:1	1:1	-
	10	45:1	18:1	-	-	-
	1	18:1	-	-	-	-
1,1,1-Trichloroethane	1000	198:1	90:1	35:1	14:1	8:1
	100	90:1	35:1	8:1	1:1	-
	10	35:1	8:1	-	-	-
	1	8:1	-	-	-	-

MATHEMATICAL CHARACTERIZATION

As a means of comparing the various performance characteristics between aeration and adsorbtion mathematical approximations over the range 90-99.99% removal have been derived. All of the approximations were based on the following equation form:

$$Y = C\,(1-Ke^{r_1 x}\, e^{r_2 x^2}) \qquad (1)$$

where

Y = % removed

K, C, r_1, r_2 = constants

x = performance characteristic

r_2 = 0 for cases of aeration

For example in the case of removing trichloroethylene by aeration:

$$Y = 100\,(1-0.31e^{-0.11x}) \qquad (2)$$

where

x = air to water ratio

But for carbon adsorption the equation for trichloroethylene removal is

$$Y = 100(1-e^{17.28-93.23x+80.67x^2}) \qquad (3)$$

where

x = % carbon use rate in lbs of carbon/1000 gal

Table 3 summarizes the parameters in equation (1) for air stripping and Table 4 summarizes the parameters for carbon adsorption. One use of these equations is to take the first derivative and compare relative performance. For aeration the first derivatives for the three equations are as follows:

Trichloroethylene - $\partial Y/\partial X = 3.41e^{-0.11X}$ (4)

Tetrachloroethylene - $\partial Y/\partial X = 4.5e^{-0.09X}$ (5)

1,1,1-Trichloroethane - $\partial Y/\partial X = .213e^{-0.03X}$ (6)

As can be seen the relative improvement by using aeration for 1,1,1-trichloroethane is less than for the other contaminants. This same type of analysis can be made for carbon adsorption.

TABLE 3

PARAMETERS FOR AIR STRIPPING

$[y = 100\ (1-Ke^{r_1 x}e^{r_2 x^2})]$

Contaminant	Parameters		
	K	r_1	r_2
Trichloroethylene	0.31	-0.11	0
Tetrachloroethlyne	0.50	-0.09	0
1,1,1-Trichloroethane	0.06	-0.03	0

TABLE 4

PARAMETERS FOR CARBON ADSORPTION

$[y = 100\ (1-Ke^{r_1 x}e^{r_2 x^2})]$

Contaminant	Parameters		
	K	r_1	r_2
Trichloroethylene	$e^{17.28}$	-93.23	+ 80.67
Tetrachloroethlyne	$e^{10.62}$	-159.87	+319.81
1,1,1-Trichloroethane	$e^{10.34}$	-19.88	+ 5.06

COST ASSUMPTIONS

The treatment cost estimates were based on the configuration shown in Figure 1. In this case, a ground water source is assumed together with one of three technologies: aeration towers; diffused-air aeration; or, granular carbon adsorption. The effluent stream from the treatment process is chlorinated, goes to a clear well, and then is distributed through high-lift pumps. In this paper, we will examine the cost tradeoffs among the three technologies assuming flows of 0.5, 1 and 10 mgd all operating at 70% capacity.[5]

The following assumptions are used for the aeration towers. The towers are assumed to be rectangular, with a height of 3 m (10 ft), with an air supply of 137 standard liters/min/sq m (52 standard cu ft/min/sq ft) of surfaced area. They are assumed to have electrically-driven induced draft bands, stacks and draft eliminators. The tower costs do not include supply pumps or underflow pumps.

Aeration basins are assumed to be rectangular, with a depth of 3.5 m (12 ft) with a diffused air supply of 14 standard liters/min/sq meter (5 standard cu ft/min/sq ft) of basin floor area.

Assumptions for adsorption were as follows: three steel contactors in series; with an initial carbon supply and carbon usage based on a six-month throwaway at a cost of $1.54/kg (.70$/lb).

The assumptions for chlorination included a feed system with no basin and a building for cylinder storage. The assumed dose is 2 mg/L and the cost of chlorine is assumed at 35¢/kg ($320/ton).

Clear well storage was assumed to be above ground and with a capacity equal to 10% of daily flow. The high-lift pump was assumed to have a head of 12 m (40 ft).

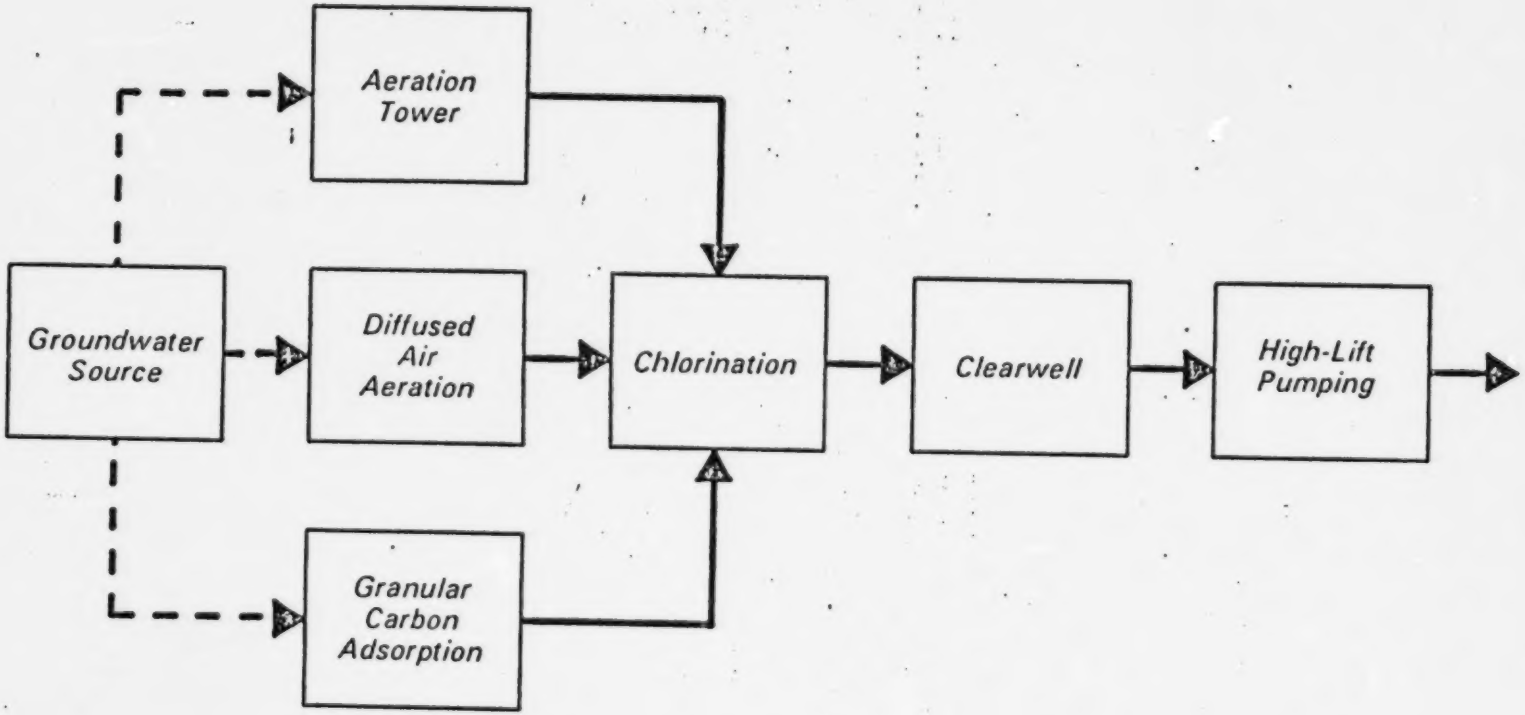

FIGURE 1 Assumed Flow Configuration for Analysis

Not included were expenditures for land, corrosion control, fences, off-gas handling, or carbon disposal. Table 5 contains specific assumptions for the .5, 1 and 10 mgd plant configurations.

TABLE 5

DESIGN ASSUMPTIONS FOR PLANT CONFIGURATIONS

		1,893m^3/day (.5mgd)	3.785 m^3/day (1.0 mgd)	37,852 m^3/day (10.0 mgd)
Clearwell Storage - Ground Level,	(gal)	50,000	100,000	1,000,000
	m^3	189	379	3,785
Chlorination Feed and Storage,	(lb/day)	58	117	1,170
	kg/day	26	53	531
High-Lift Pumping Head,	(ft)	40	40	40
	m^3	12	12	12
Cost of Labor		$9.00/hour		
Cost of Electricity		$.05/kilowatt-hour		
Amortization Interest Rate		10%		
Amortization Period		20 years		
ENR Construction cost Index (1982)		361		

Typical of the basic data used in generating these estimates are the cost curves shown in Figures 2 and 3.[5] Figure 2 shows the construction cost in dollars versus a design parameter which is cubic feet of volume. Figure 3 shows various O&M costs vs. the total surface area in square feet. Dollars are based on 1978 for construction, energy, labor, and maintenance material costs, and can be updated for current costs.

Using these cost data, the given preliminary design assumptions and the performance data listed in the previous section cost comparions for the three technologies to remove trichloroethylene, tetrachloroethylene and 1,1,1-trichlroethane were calculated.

Figures 4, 5 and 6 show the costs for removing trichloroethylene at the 0.5, 1 and 10 mgd design levels. Calculations are made for removals from 90 to 99.99%. As might be expected the unit costs for all three technolgies drop with increasing design capacity. Costs increase with decreasing target concentration. Carbon adsorption becomes somewhat less expensive than basin aeration with increasing design capacity. At all design levels and for all removals assuming an initial concentration of 1000 ug/L, aeration is the lowest cost technology.

Figures 7, 8 and 9 show the costs associated with removing tetrachloroethylene under the same conditions. As before tower aeration is least expensive at all levels of removal. In this case carbon adsortpion is consistently less expensive than diffused aeration.

Figures 10, 11, and 12 show the costs associated with 1,1,1-trichloroethane removal. In this case tower aeration is much less expensive for all levels of contaminant removal.

Table 6 summarizes the costs developed in Figures 4 through 12 at removal levels of 90%, 99%, 99.9% and 99.99%.

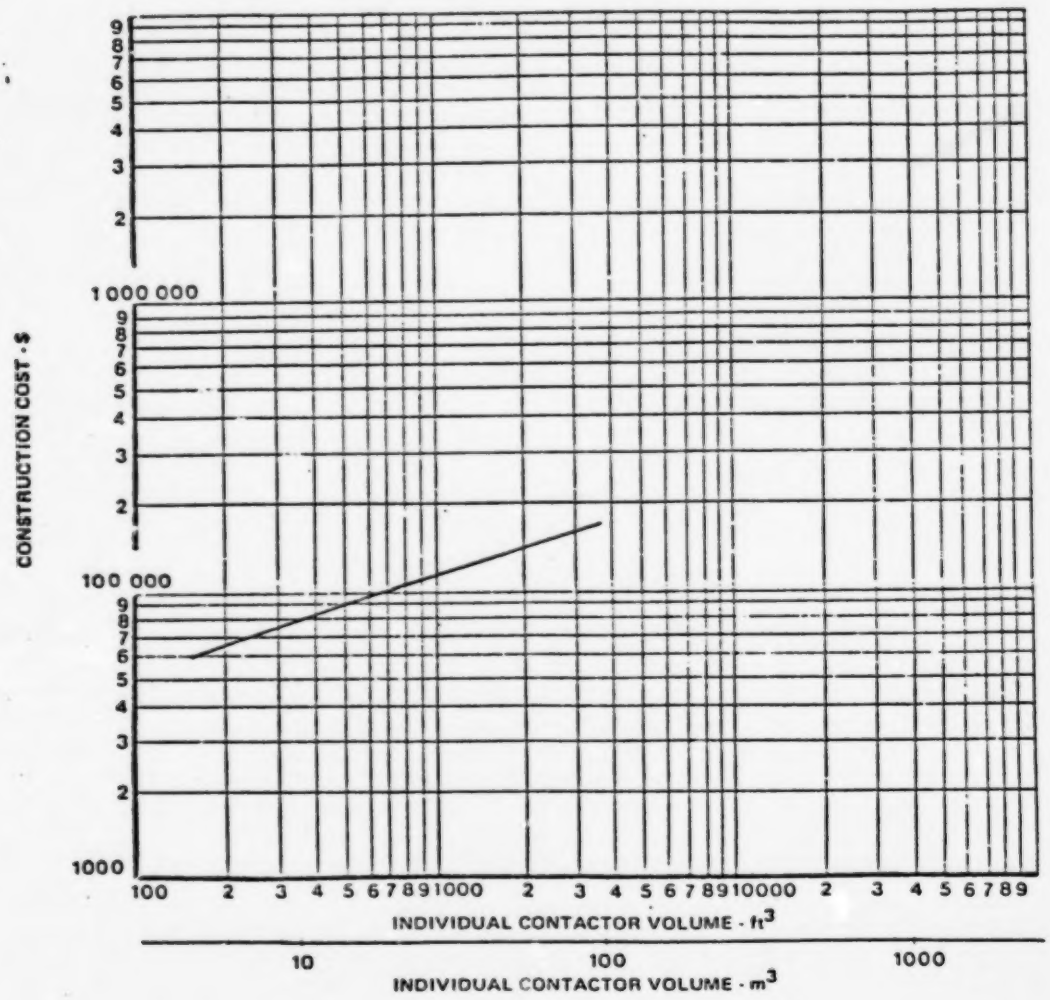

FIGURE 2 Construction Cost Data

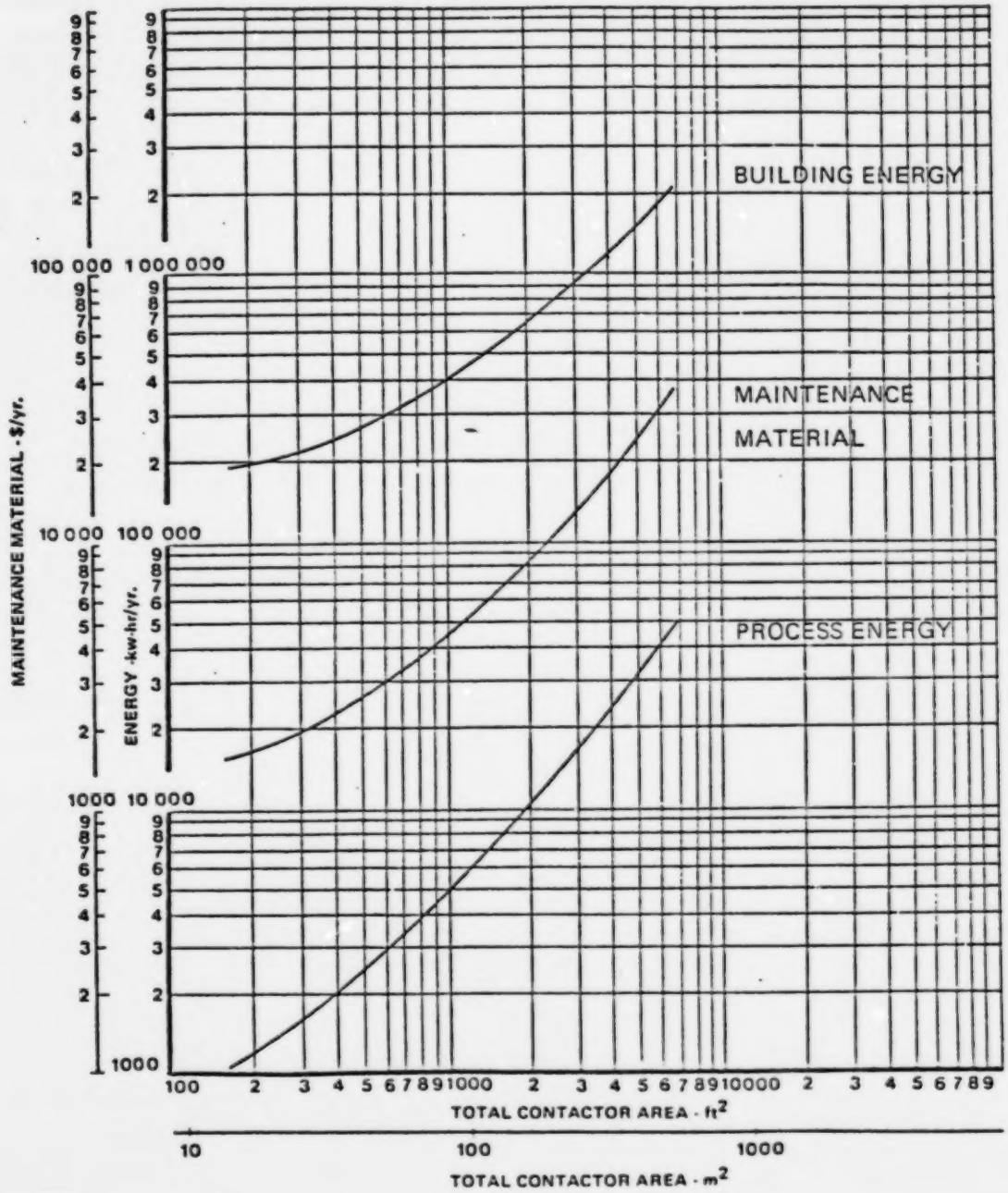

FIGURE 3 Operation and Maintenance Cost Data

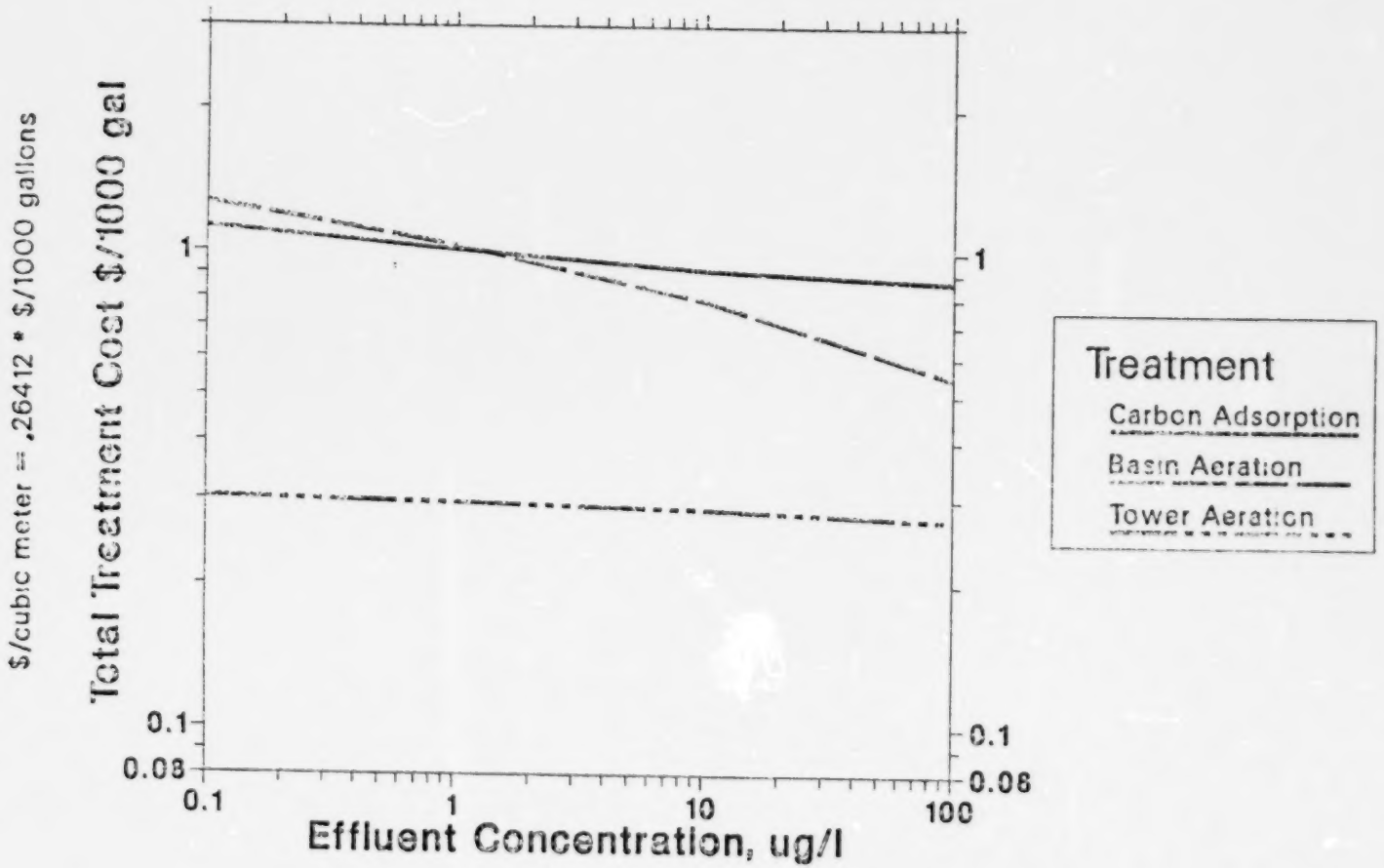

Figure 4: Trichloroethylene 0.5 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

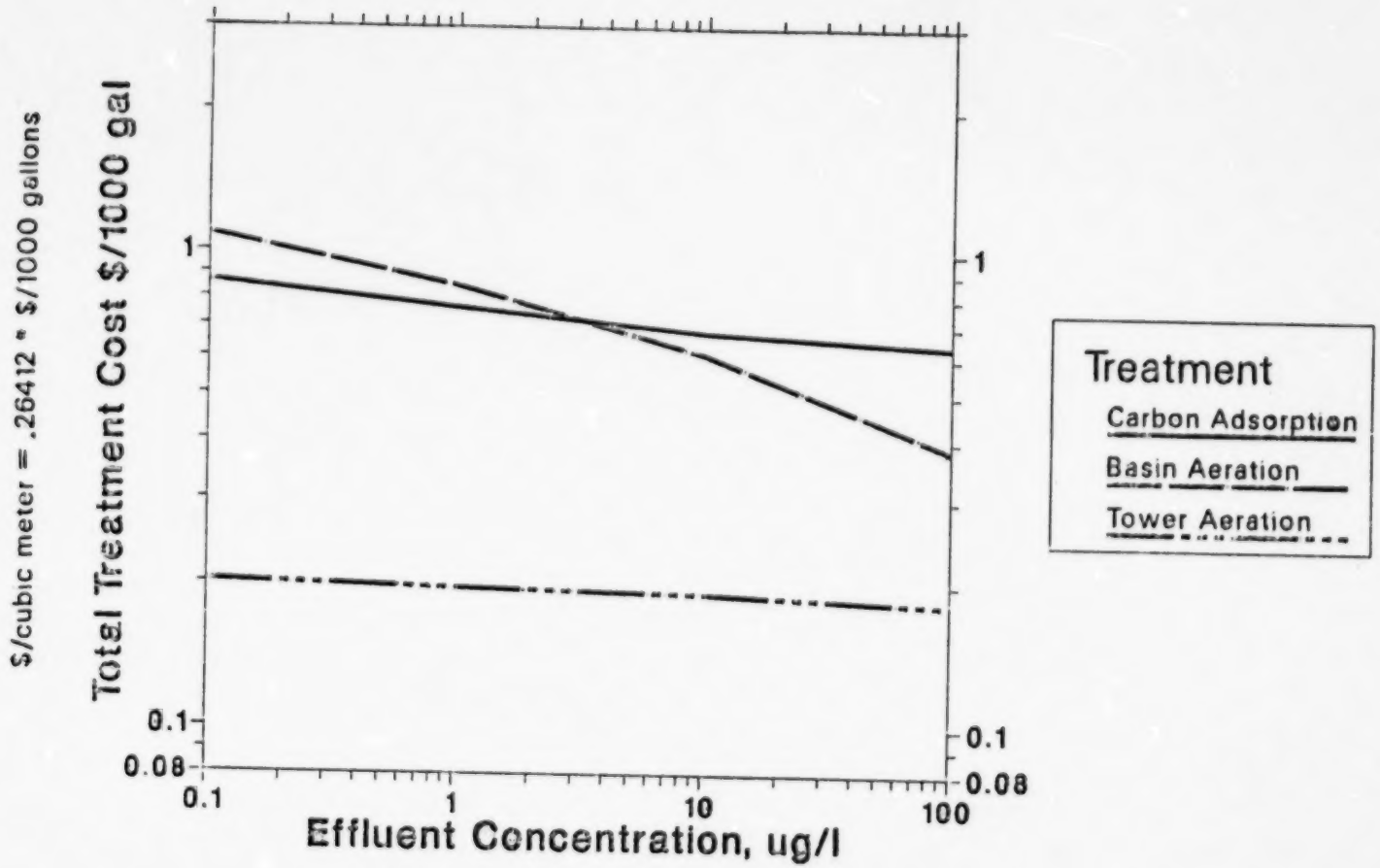

Figure 5: Trichloroethylene 1.0 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

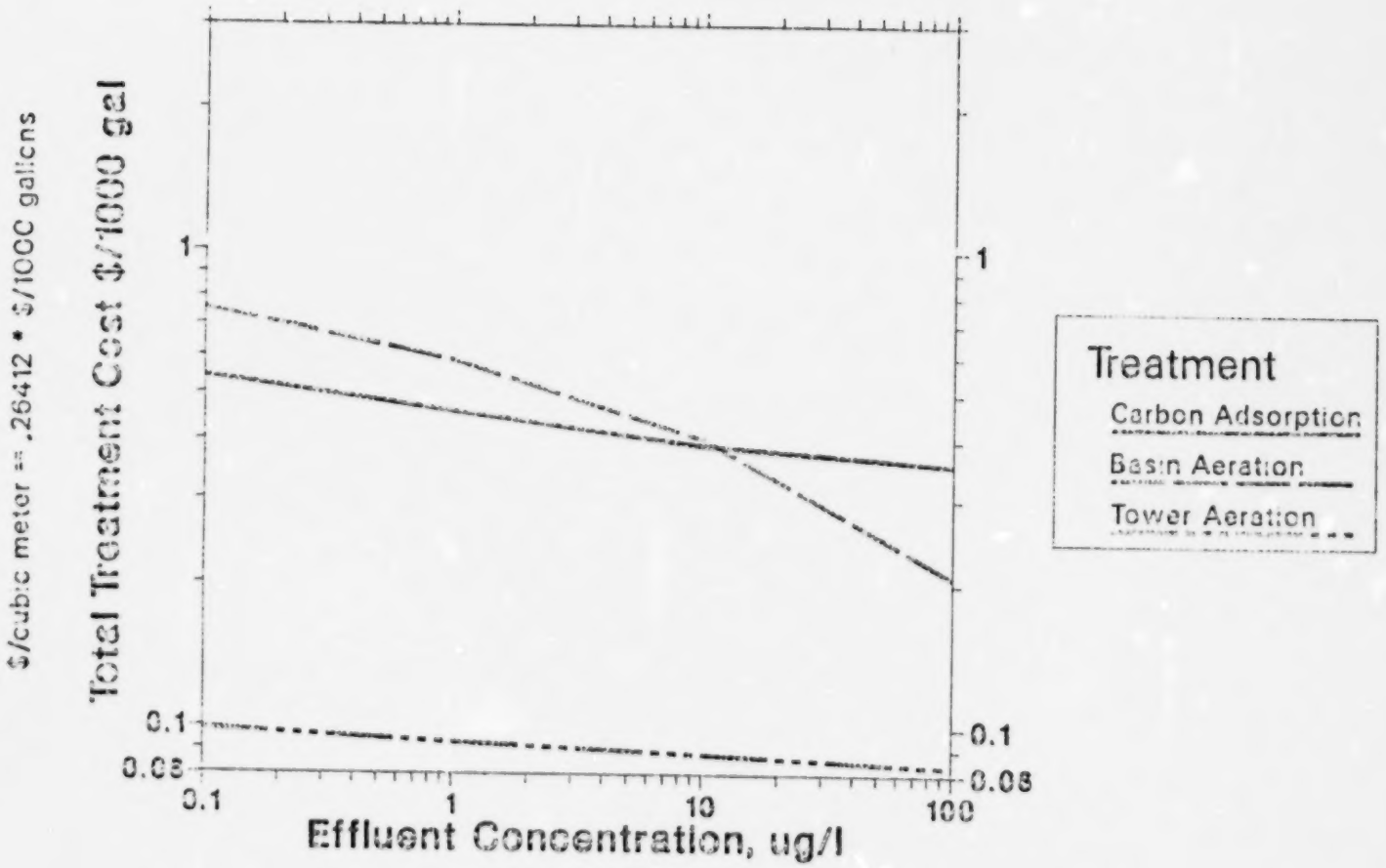

Figure 6: Trichloroethylene 10 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

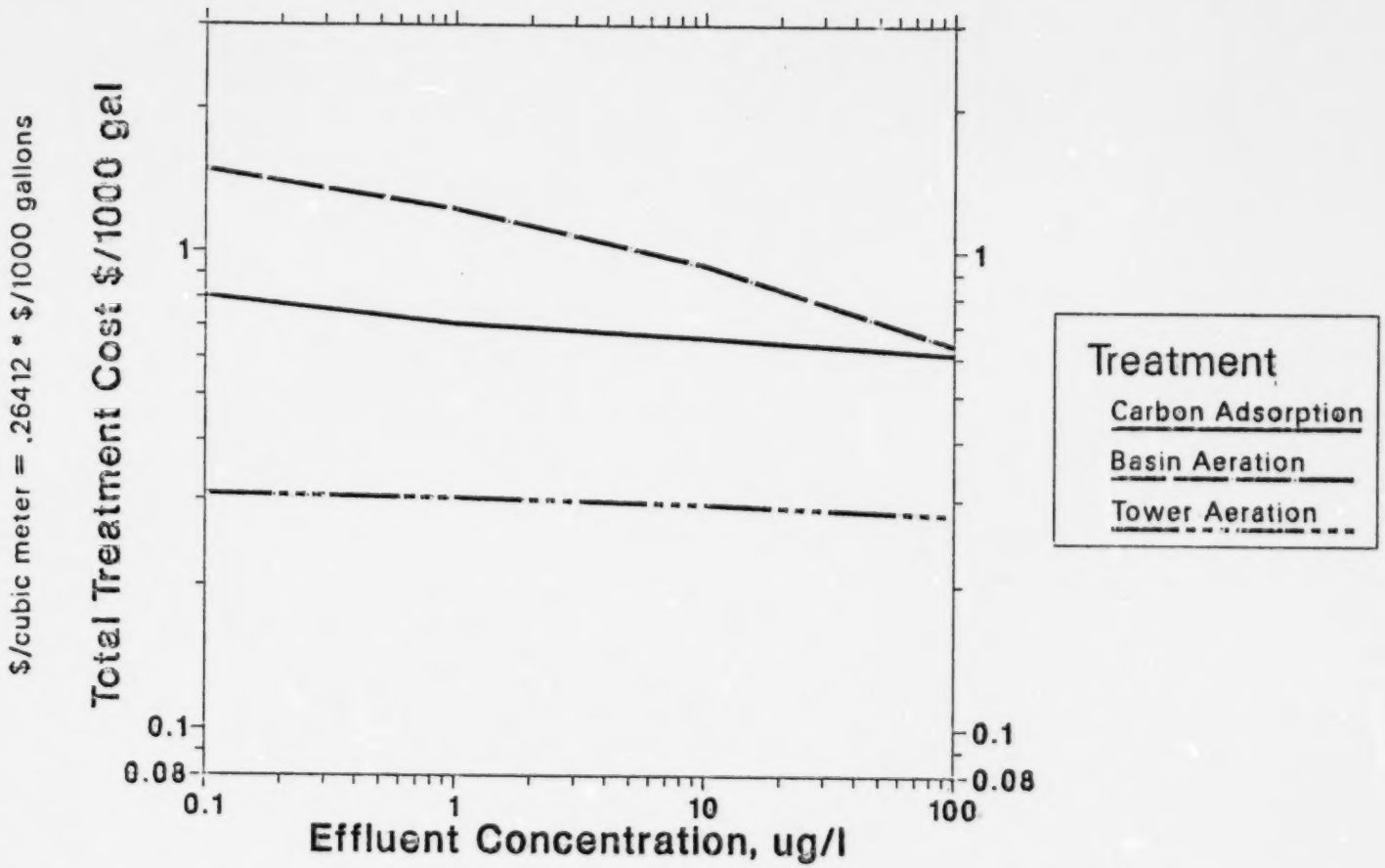

Figure 7: Tetrachloroethylene 0.5 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

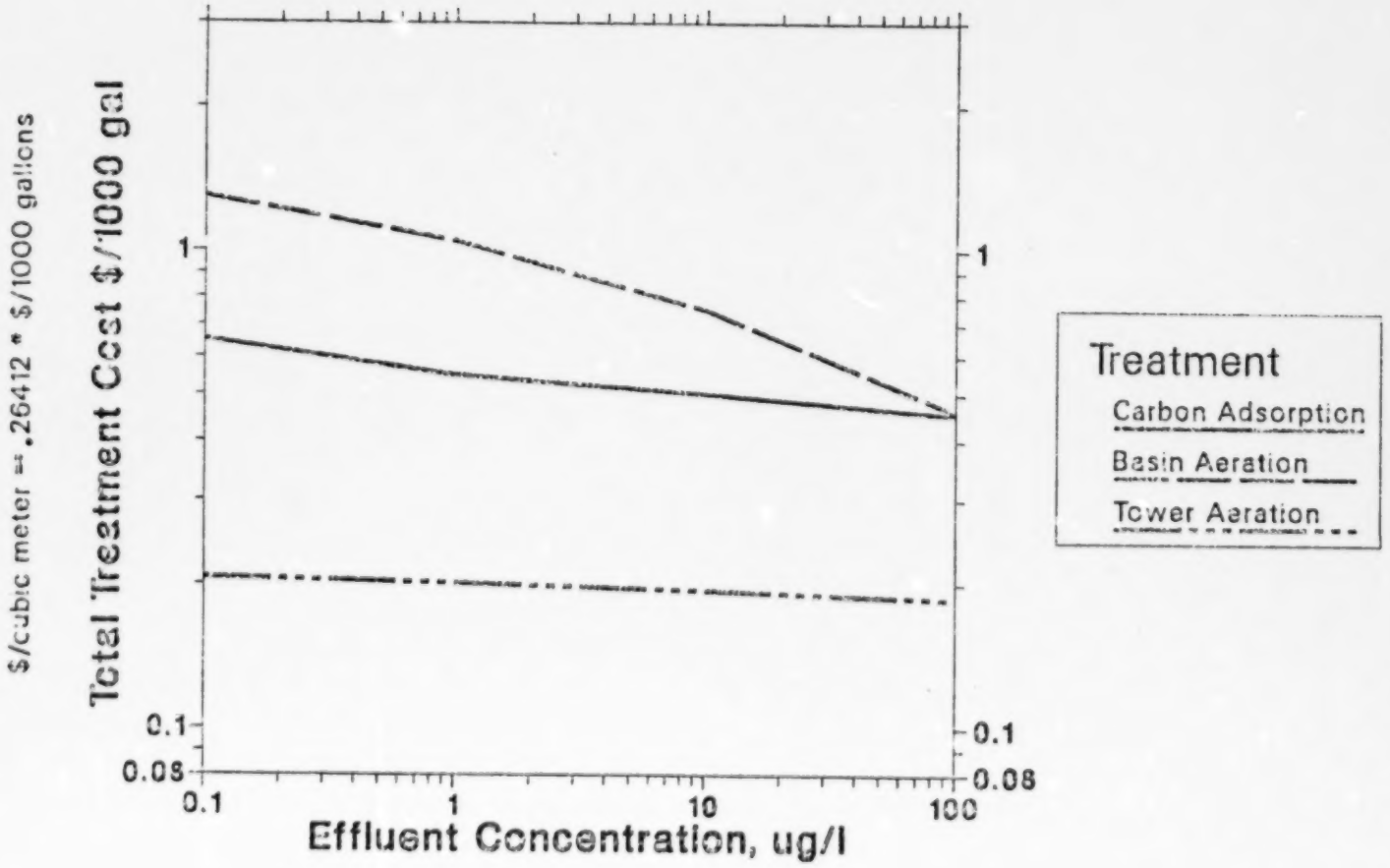

Figure 8: Tetrachloroethylene 1.0 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

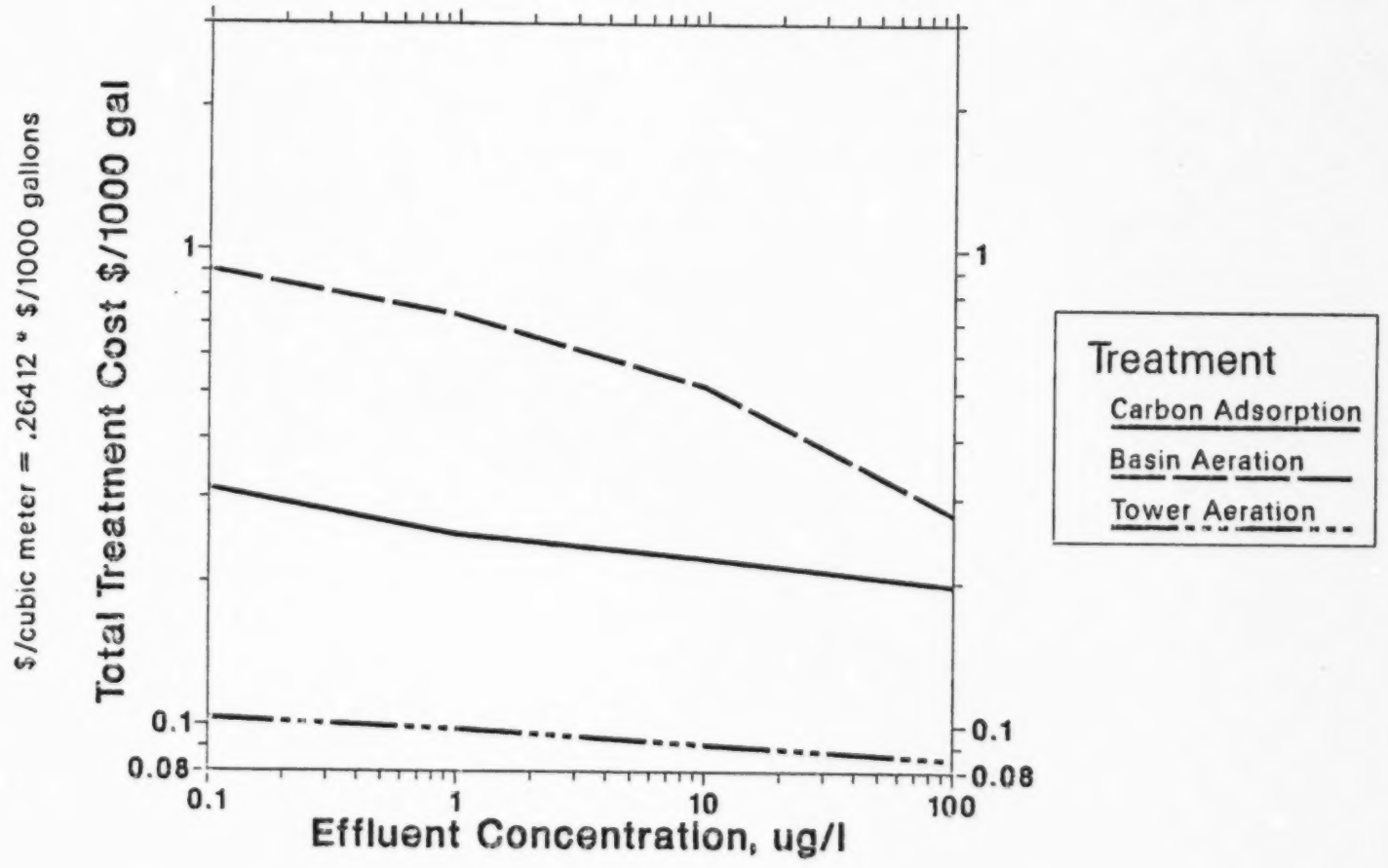

Figure 9: Tetrachloroethylene 10 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

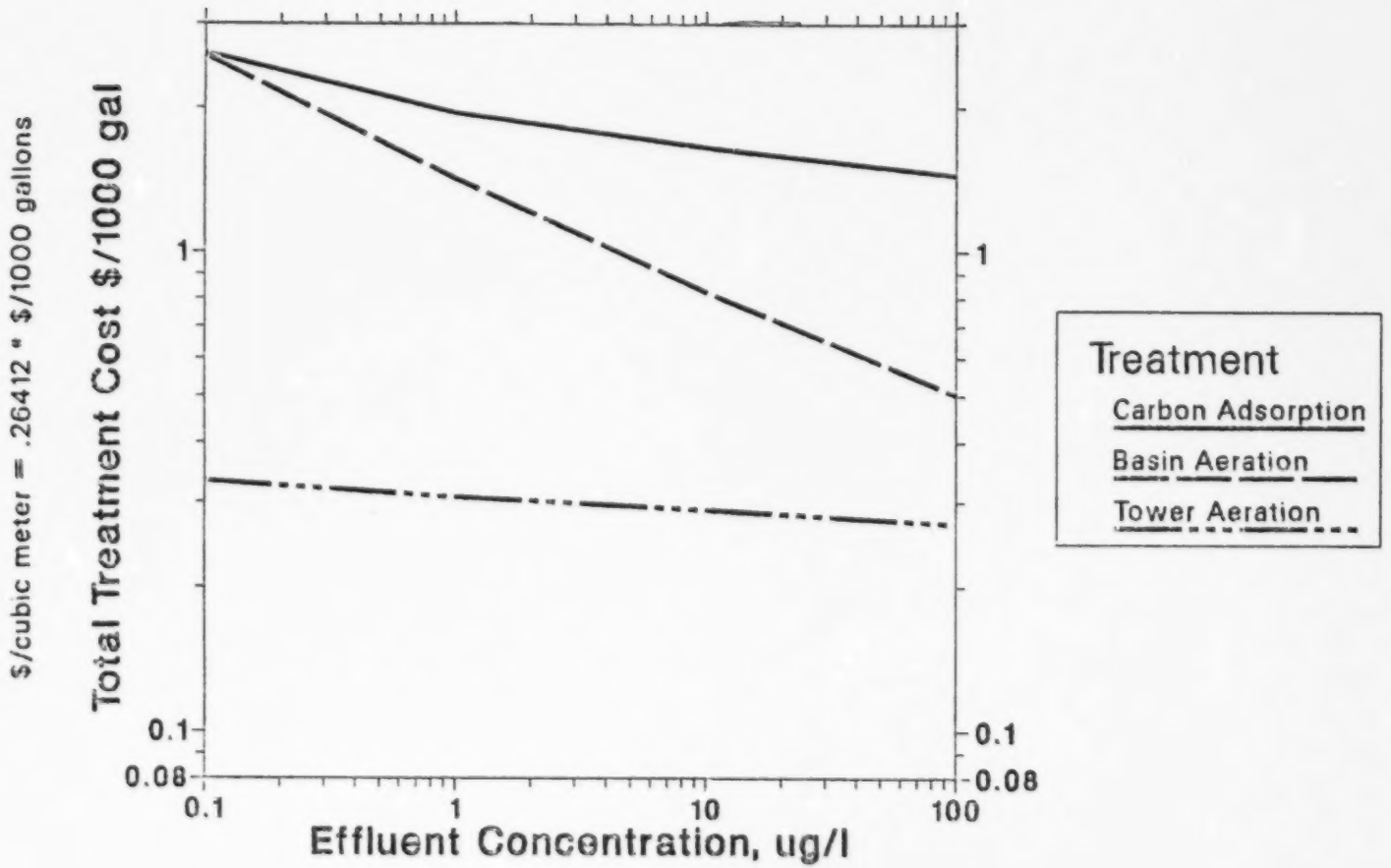

Figure 10: 1,1,1-Trichloroethane 0.5 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

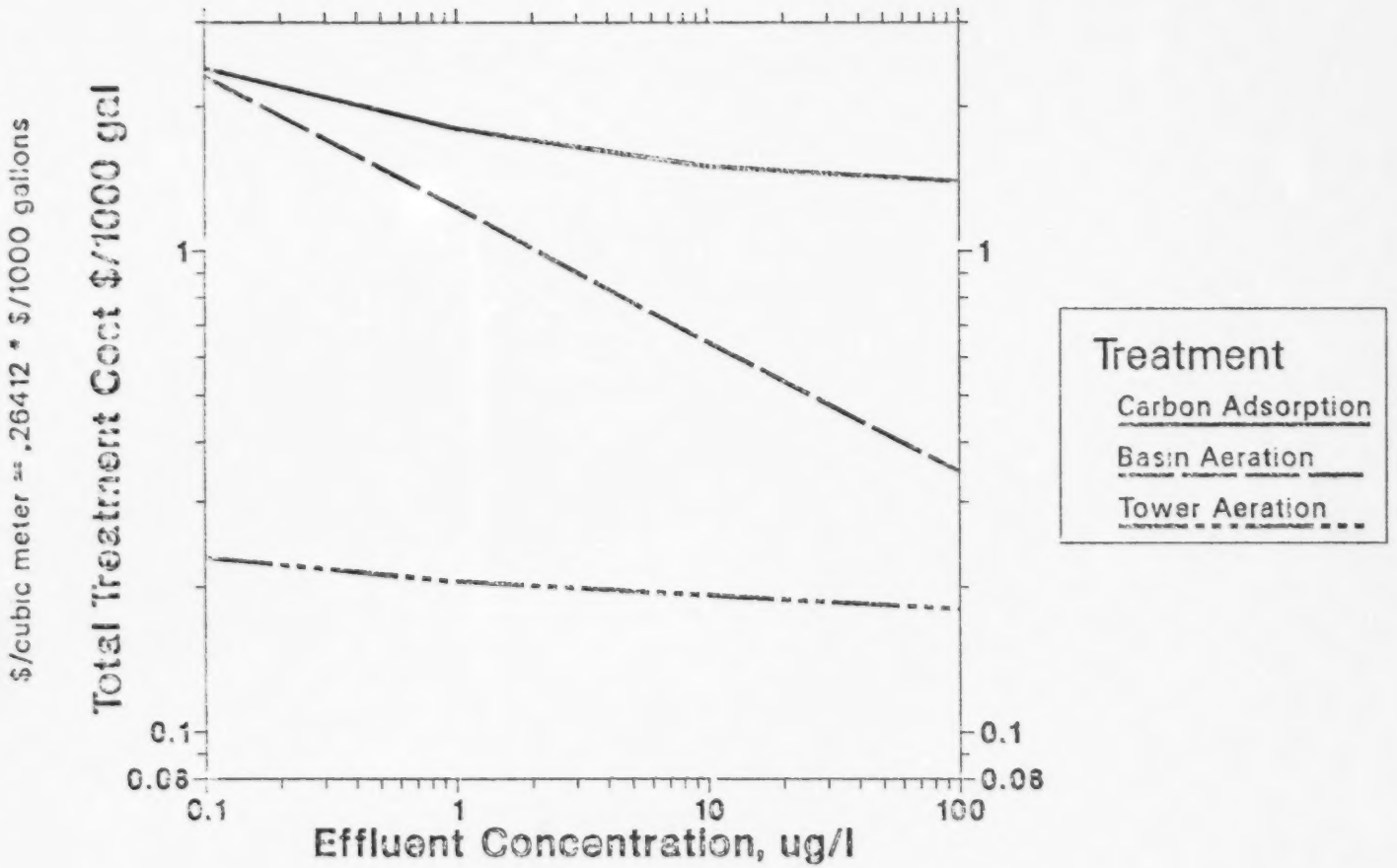

Figure 11: 1,1,1-Trichloroethane 1.0 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

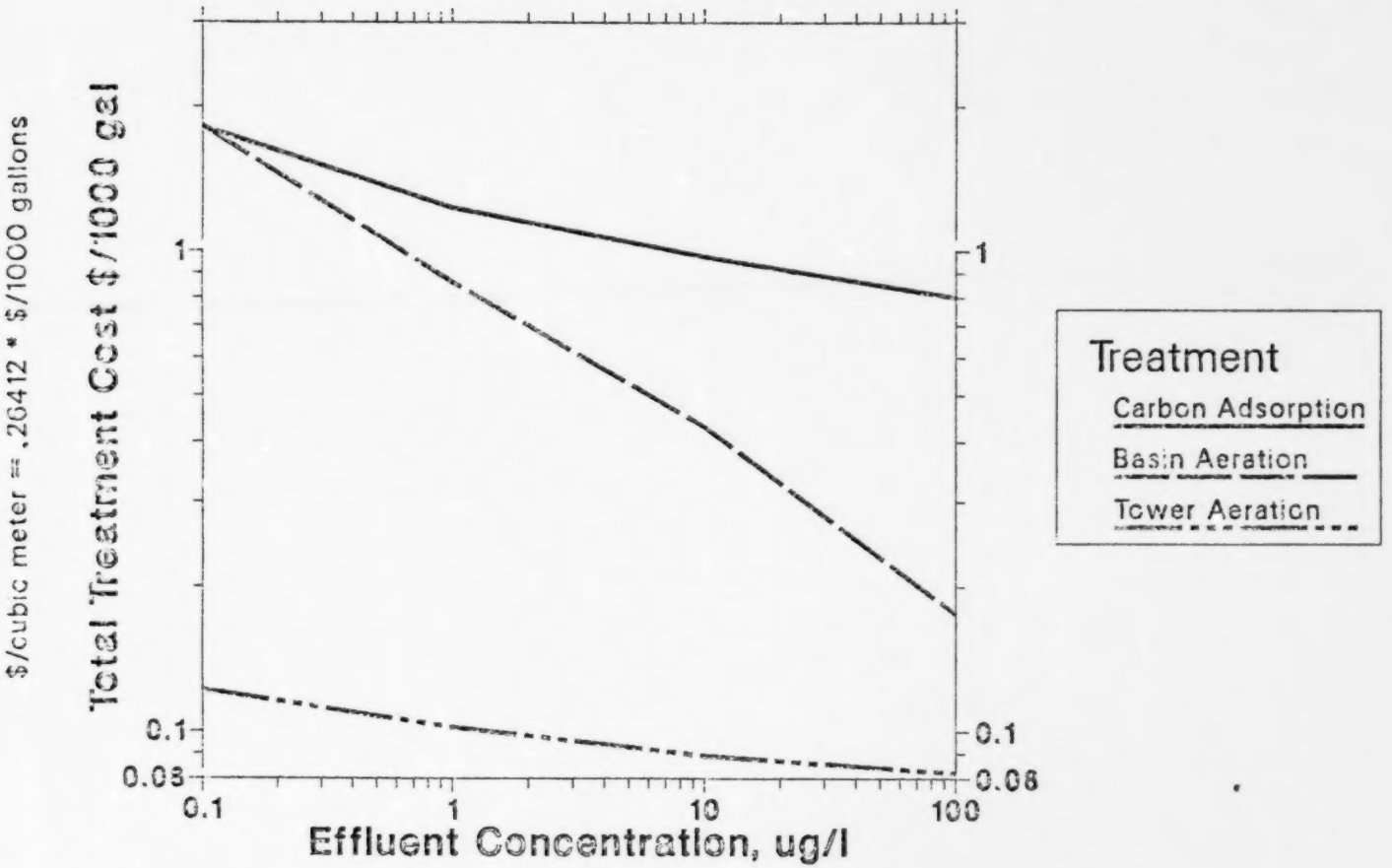

Figure 12: 1,1,1-Trichloroethane 10 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

TABLE 6

COST DATA SUMMARY (VOC Removal Costs)

Contaminant	Facility Size (mgd)	ug/L	% Removal	Tower, $/1000 gal	Basin, $/1000 gal	Carbon, $/1000 gal
Trichloroethylene	0.5	100	90	.273	.546	.868
		10	99	.287	.793	.918
		1	99.9	.296	1.032	1.010
		.1	99.99	.303	1.270	1.124
Trichloroethylene	1.0	100	90	.182	.383	.637
		10	99	.191	.611	.679
		1	99.9	.196	.850	.765
		.1	99.99	.202	1.088	.867
Trichloroethylene	10.0	100	90	.083	.207	.356
		10	99	.088	.403	.390
		1	99.9	.093	.587	.458
		.1	99.99	.099	.755	.543
Tetrachloroethylene	0.5	100	90	.279	.637	.610
		10	99	.293	.935	.660
		1	99.9	.302	1.228	.705
		.1	99.99	.308	1.486	.805
Tetrachloroethylene	1.0	100	90	.186	.460	.453
		10	99	.194	.752	.502
		1	99.9	.201	1.046	.548
		.1	99.99	.206	1.296	.651
Tetrachloroethylene	10.0	100	90	.085	.277	.197
		10	99	.091	.514	.224
		1	99.9	.098	.726	.251
		.1	99.99	.103	.905	.313
1,1,1-Trichloroethane	0.5	100	90	.270	.502	1.445
		10	99	.289	.825	1.651
		1	99.9	.307	1.421	1.945
		.1	99.99	.332	2.572	2.605
1,1,1-Trichloroethane	1.0	100	90	.180	.348	1.396
		10	99	.192	.644	1.500
		1	99.9	.205	1.234	1.801
		.1	99.99	.230	2.313	2.402
1,1,1-Trichloroethane	10.0	100	90	.082	.176	.802
		10	99	.089	.430	.973
		1	99.9	.102	.860	1.229
		.1	99.99	.122	1.821	1.818

In the next section some strategies for minimizing the cost of adsorption will be considered based on the strategies of regional reactivation and the possible installation of home units for adsorption.

COST MINIMIZATION OPTIONS

In this section two options will be considered as alternatives to minimize the cost of volatile organic contaminant removal. The first is regionalization, which assumes that the cost of carbon can be minimized by sharing the costs of reactivation among several utilities. The two sloping lines in Figure 13 represent the cost of carbon with and without reactivation for trichloroethylene at 99% removal. The Regional reactivation option would lie somewhere in this envelope. The three horizontal lines represent home treatment units with three different GAC cartridge replacement cycles.[6] In this case separate inhouse units are assumed based on the costs in Table 7.

TABLE 7

ASSUMPTIONS FOR HOME UNIT ADSORPTION

Flow:	.0303 m^3/family/day (8 gal/family day)
Cost of Unit:	$250
Installation Cost:	$50
Design Life	10 yrs
Quarterly Sample	$15
Replacement Cartridge:	$50
Volume of Flow:	0.0071 m^3 (0.25 ft^3)

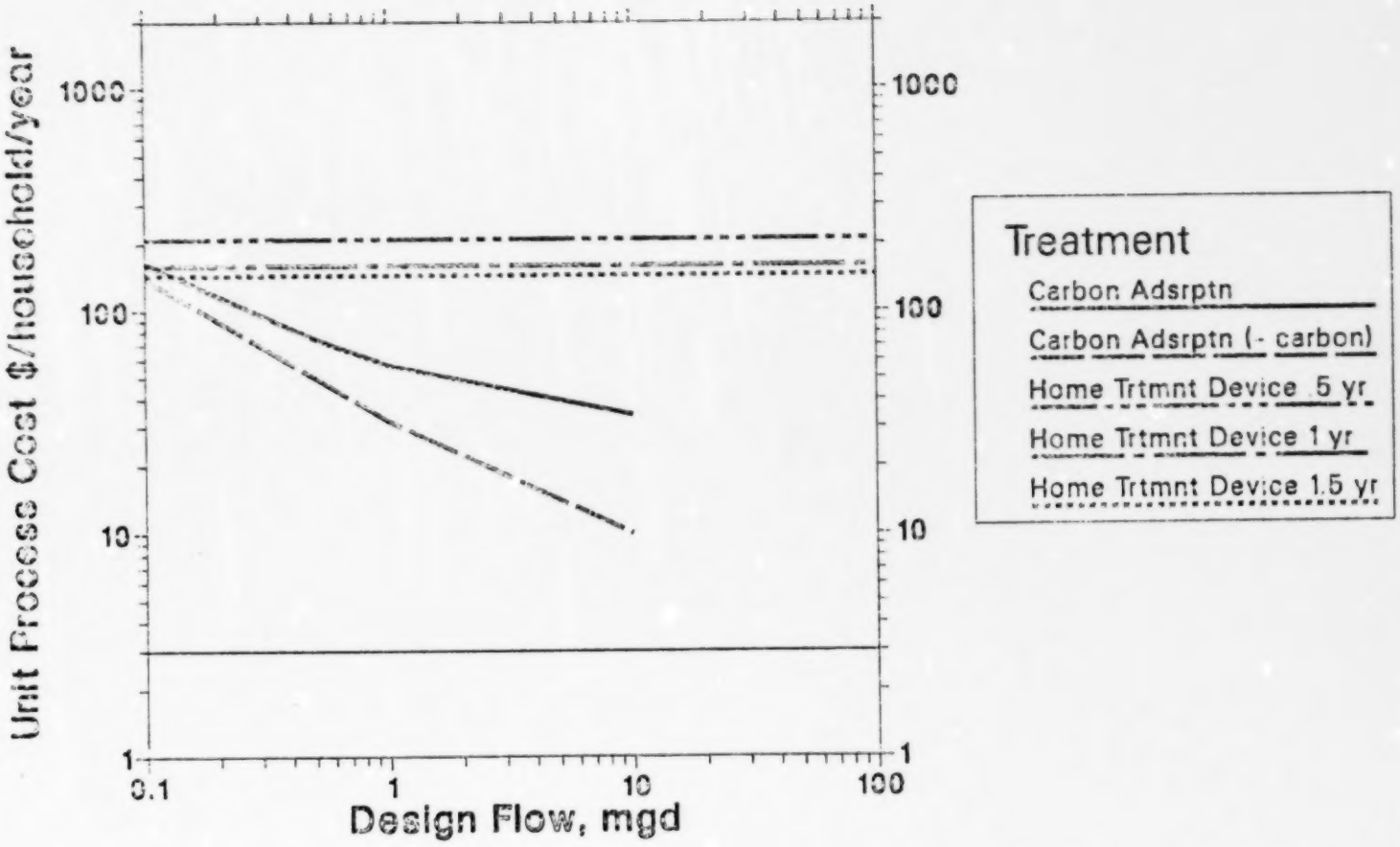

Figure 13: Trichloroethylene 99% Removal
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

In this section costs are based on a direct comparison of technology as opposed to system costs calculated in the previous section. The costs are also based on a $/family/yr basis

The flow for the home units is as shown in Table 7 but the flows for the other technologies are based on an assumed flow of 300 gallons per family per day.

Figures 14 and 15 show the costs associated with home treatment (replacement at 1/yr), basin aeration, carbon adsorption (assumed at midpoint of envelope of cuves) and tower aeration for removing trichloroethylene. Costs are calculated at the 0.1 and 0.5 mgd level for 90-99.99% removal.

As with the previous analysis aeration is consistantly the least costly technology. However at 0.1 mgd the home unit devices become competitive with the carbon regionalization option. Therefore, for high molecular compounds which may not be amendable to air stripping, individual home adsorption units may be cost-effective. Table 8 summarizes these costs at 90%, 99.0%, 99.9% and 99.99% removal.

Table 8

COST DATA SUMMARY FOR TRICHLOROETHYLENE (Cost Saving Options)

Facility Size	ug/L	% Removal	$/household/year Tower	Basin	Carbon	HTD*
.1 mgd	100	90	11.3	50.0	145.1	160.0
	10	99	15.8	96.9	153.1	160.0
	1	99.9	18.6	128.7	167.5	160.0
	.1	99.99	20.8	166.5	183.3	160.0
.5 mgd	100	90	3.8	33.7	58.4	160.0
	10	99	5.4	60.9	62.3	160.0
	1	99.9	6.4	87.1	69.3	160.0
	.1	99.99	7.1	113.1	77.9	160.0

*Home treatment devices.

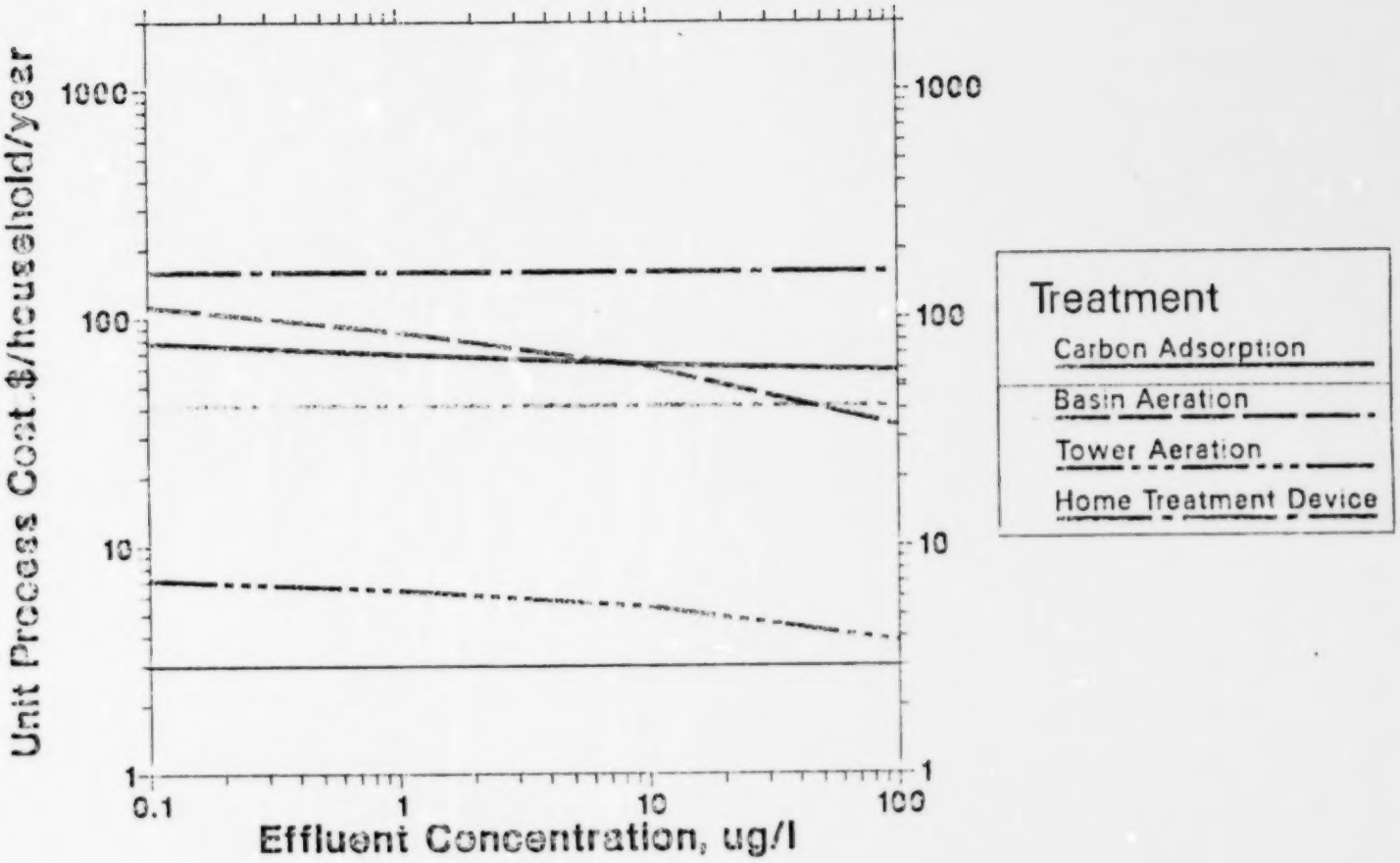

Figure 14: Trichloroethylene 0.5 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

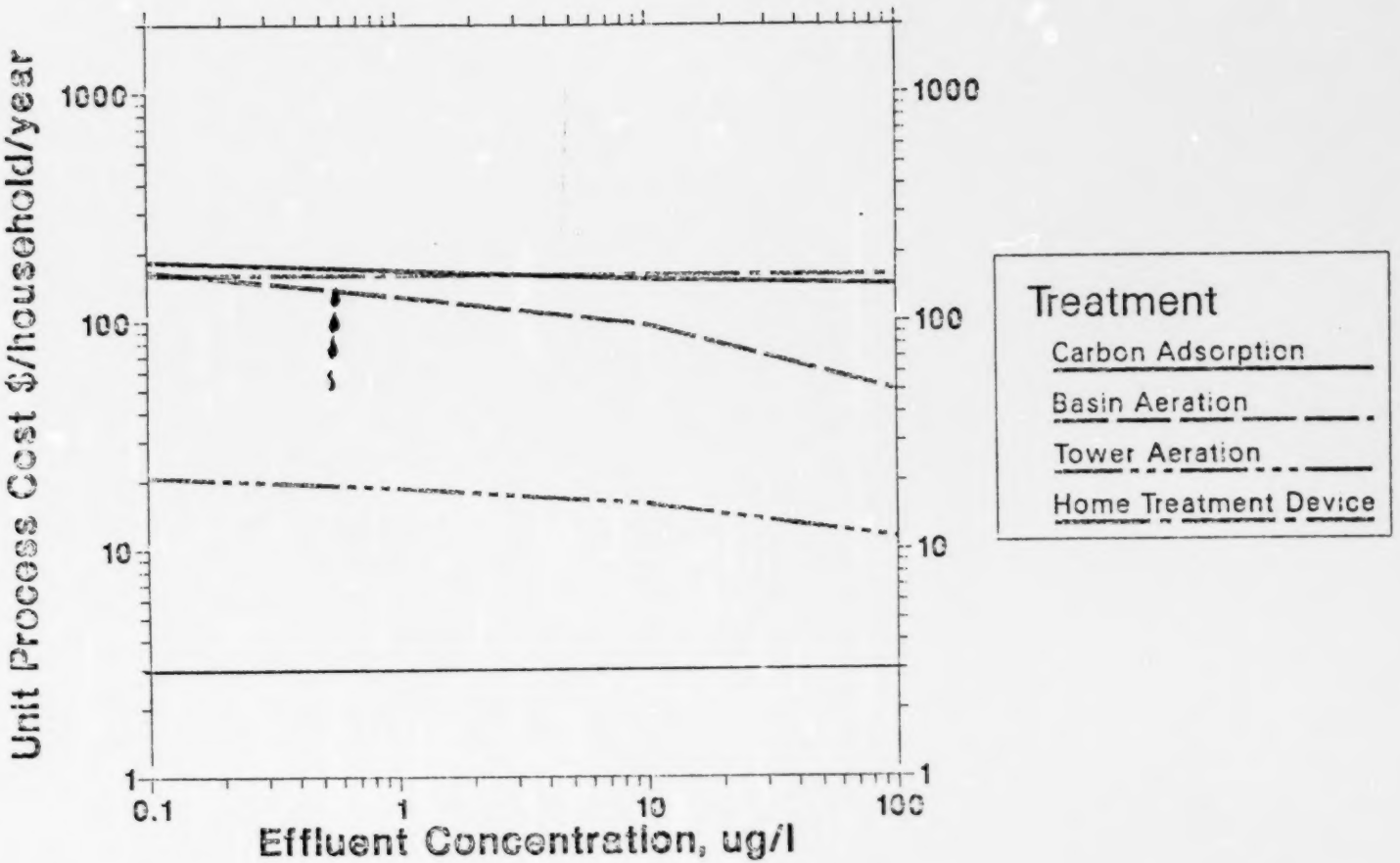

Figure 15: Trichloroethylene 0.1 mgd
Influent Concentration = 1000 ug/l
Sept. 82 Dollars

MARGINAL COSTS OF REMOVAL

As may be observed from Table 1, the required carbon use rate changes with influent concentration level and the contaminant to be removed. The air to water ratio for removal remains constant for a given removal efficiency. This phenomenon suggests that some combination of air stripping and adsorption might be cost effective. Perhaps tower aeration could accomplish the bulk of the stripping with carbon adsorption as a finishing step. Figures 16, 17 and 18 show the costs for 90% removal of the 0.5 mgd level for all three technologies and contaminants. As can be seen at the lowest influent concentration levels, carbon cost is close to the cost of air stripping, but not less than tower aeration. Table 9 summarizes these costs at 90%, 99%, 99.9% and 99.99%.

TABLE 9

COST DATA SUMMARY (Marginal Cost)

Contaminant	ug/L	% Removal	Tower $/1000 gal	Basin $/1000 gal	Carbon $/1000 gal
Trichloroethylene	1	90	.27	.55	.46
	10	90	.27	.55	.53
	100	90	.27	.55	.64
	1000	90	.27	.55	.87
Tetrachloroethylene	1	90	.28	.64	.39
	10	90	.28	.64	.43
	100	90	.28	.64	.49
	1000	90	.28	.64	.61
1,1,1-Trichloroethane	1	90	.27	.50	.43
	10	90	.27	.50	.51
	100	90	.27	.50	.75
	1000	90	.27	.50	1.44

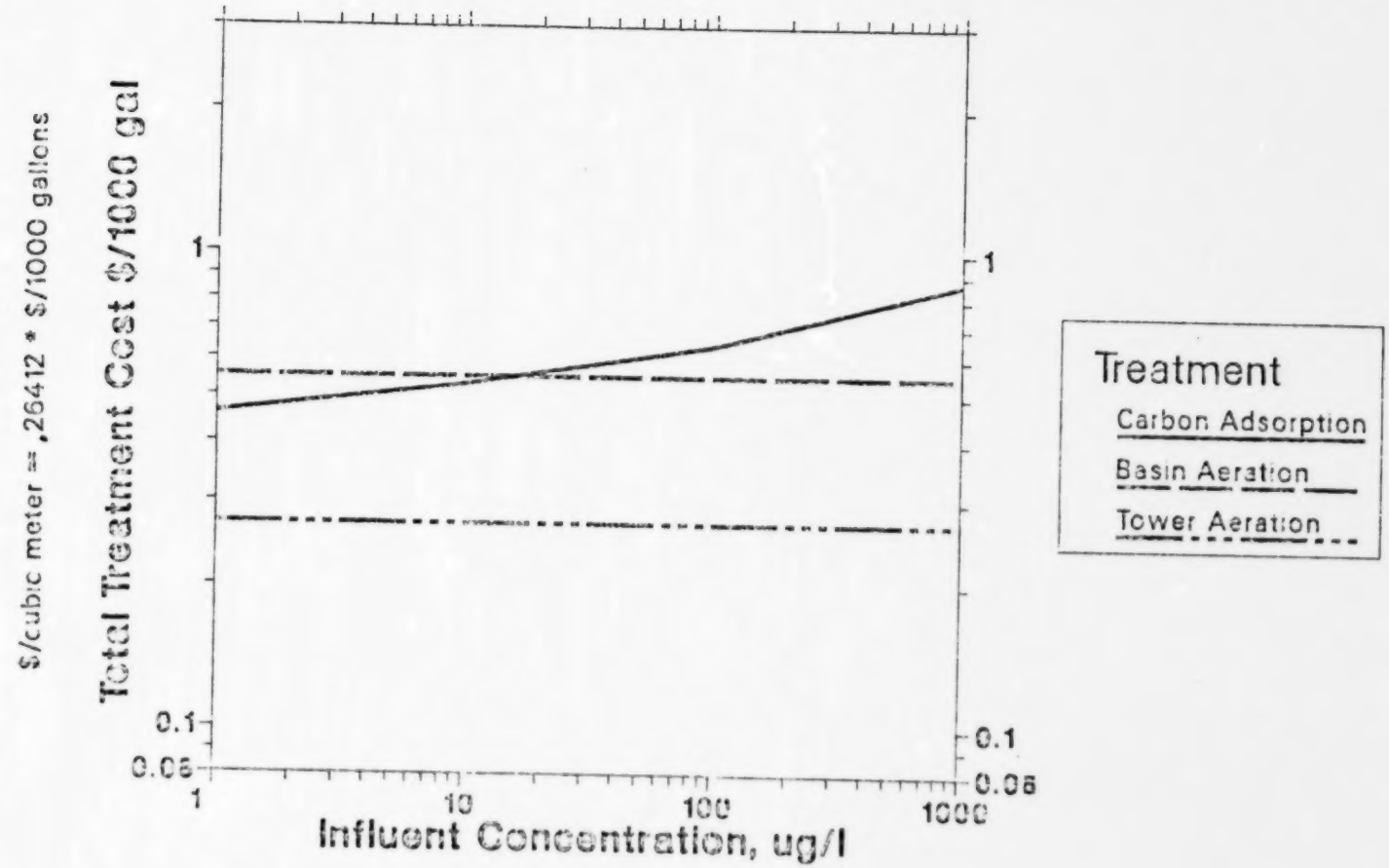

Figure 16: Trichloroethylene 90% Removal 0.5 mgd

Sept. 82 Dollars

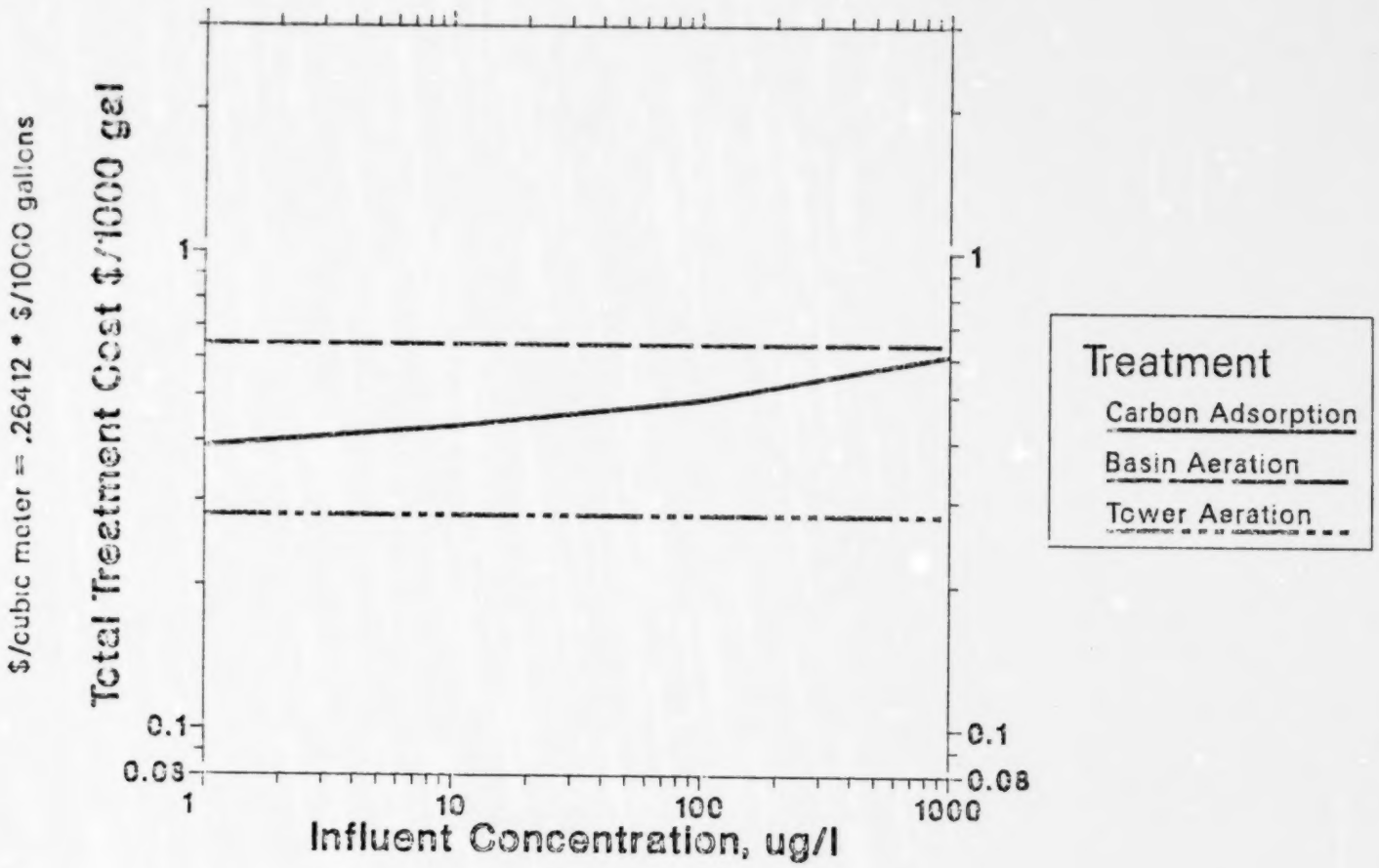

Figure 17: Tetrachloroethylene 90% Removal 0.5 mgd

Sept. 82 Dollars

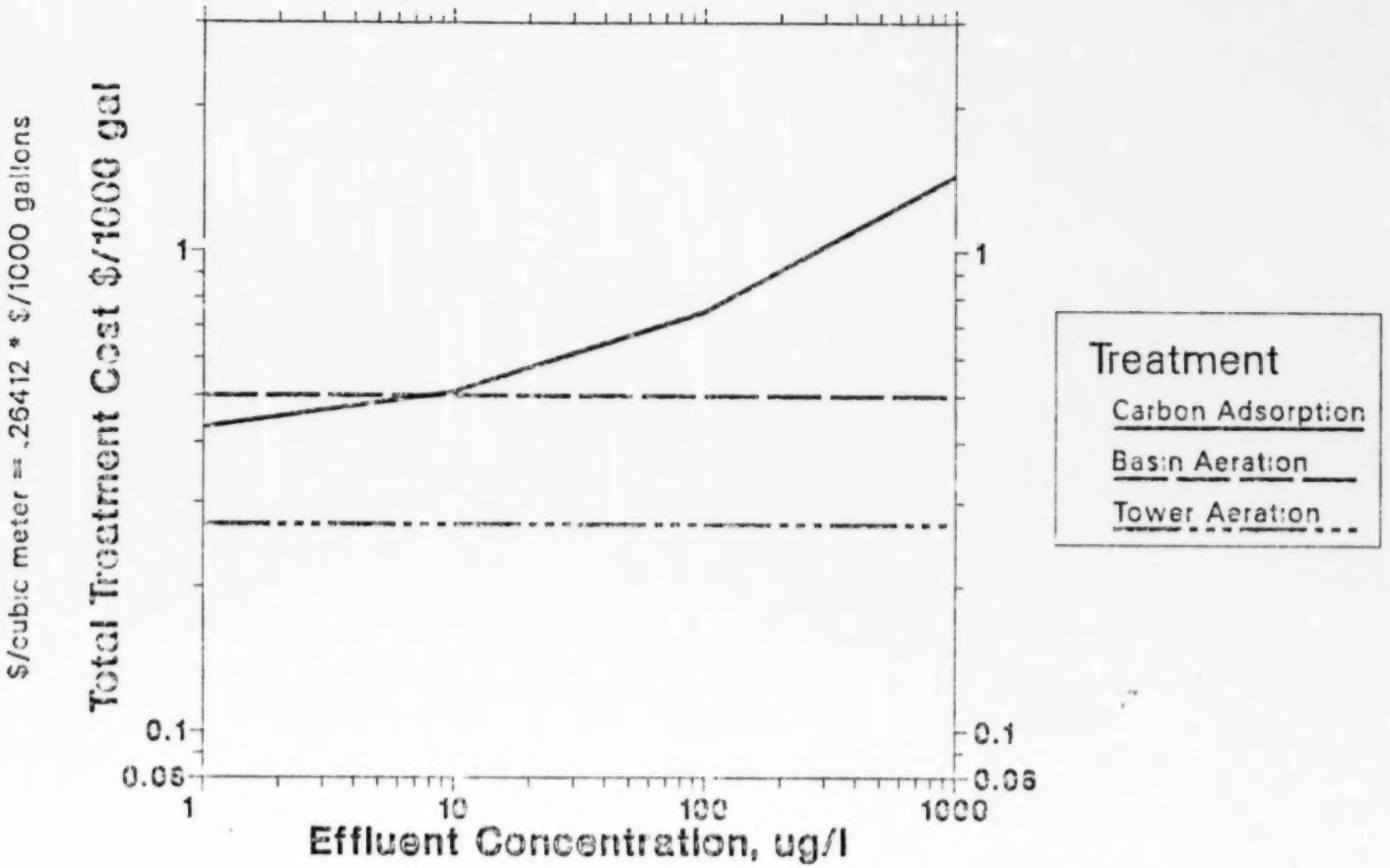

Figure 18: 1,1,1-Trichloroethane 90% Removal 0.5 mgd

Sept. 82 Dollars

SUMMARY AND CONCLUSIONS

It is concluded from the previous analysis that, where feasible, tower aeration is by far the cheapest technology. It is also the cheapest technology over a wide range of removal percentages. However, there may be cases where aeration is not effective. For example in the case of removing higher weight molecular compounds, adsorption is the probable technology of choice. At the smallest sizes, home adsorption units may be cheaper than central adsorption treatment. Field research in the future should concentrate on developing the elements of the performance matrix for the options of aeration, and adsortpion and to verify costs through case studies and to identify where the technologies discussed should be applied.

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